# PROJECT RULISON - SUMMARY OF RESULTS AND ANALYSES


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Presented at

American Nuclear Society Winter Meeting
October 1971

Miami, Florida


Some of the material or interpretations presented in this paper may be revised in the future depending on additional data or information developed in connection with Project Rulison.

## DISCLAIMER

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E R R A T A

October 11, 1971 - Figure 1. The flow rate at the conclusion of the third production test should be shown as being approximately 900 MCFD, not zero as indicated.

# PROJECT RULISON - SUMMARY OF RESULTS AND ANALYSES

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## I. INTRODUCTION

Project Rulison, the second Plowshare experiment co-sponsored by industry and government, was designed to determine the potential of using nuclear stimulation technology for the development of the gas bearing Mesaverde formation in the Rulison Field of Garfield County, Colorado.(1)

On September 10, 1969, a nuclear explosive with a nominal yield of 40 kilotons was detonated at Project Rulison, 8426' below the surface.

Re-entry drilling operations designed to achieve an effective communication with the chimney and fracture system created by the nuclear explosive were initiated in April, 1970. A successful penetration of the fractured zone near the top of the chimney was made in July, 1970, and the well completed for production testing.(2)

From the post-shot drilling experience, it was estimated that the rubble filled chimney was approximately 350' in height. This is greater than the minimum 301' that was predicted, but compatible with the associated cavity radii dimensions determined from well test data which are discussed in Section II and III below.

Testing of the nuclear stimulated well was initiated in October, 1970, and after four intermittent flow periods was concluded in April, 1971.

## II. FLOW TESTS

First flows from the nuclear stimulated well were made at rates varying from 2 million to 16 million standard cubic feet of gas per day (MMSCFD). These tests spanned a three day period of time and were made for the purpose of "calibrating" the U.S. Public Health Service offsite surveillance program.[3] Tracking and measurement of the gaseous radioactive effluents were carefully done in order to confirm that the production testing program which was to follow could be carried out with assurance that the health and safety of the nearby population would be protected.[4]

Following the calibration flow period, three production flow tests were made for the purpose of determining the post-shot production characteristics of the Mesaverde formation in the interval stimulated by the nuclear explosive. Figure 1 shows the flow rates and volumes of gas produced for each of these test periods.

A total of approximately 455 MMSCF of gas, including certain diluents which were present, was produced from the nuclear stimulated well in 108 days of flow testing. This volume is the equivalent of approximately 10 years of production from a conventionally stimulated well in the Rulison Field. The 455 MMSCF of gas was saturated with water vapor at separator conditions and was diluted with carbon dioxide and hydrogen. The behavior of these diluents with time is described below under "Gas Analysis Data" and "Evolution and Production of Water Vapor and Carbon Dioxide".

Subsurface pressure and temperature measurements were made at a measured depth of 8200', a point 154' above the bottom of the re-entry well or 346' above the detonation point. The first such measurement was made on October 24, just prior to the first production test, with a shut-in pressure of 3150 psig being recorded. These subsurface measurements could not be made during the calibration flow period, the first production test, or the early part of the third production test because of the high velocity of flow in the tubing string. In order to complete this subsurface pressure data, daily pressures were computed from surface pressure measurements using observed subsurface pressures to calibrate the computations. A plot of the computed and measured bottom hole pressures by days from the commencement of testing on October 4, 1970, to August 1, 1971, is shown in Figure 2.

Analysis of the bottom hole pressures measured during the second production flow test indicated no restriction to flow through the penetrated fractures, thus confirming that an effective communication with the chimney had been established by the re-entry wellbore. This observation was particularly important because of the initial concern that the intersection of fractures only by the re-entry wellbore might not be sufficient for production testing purposes. A simple p-v-t analysis of these pressures also indicated a cavity radius of approximately 76', which compares favorably with radii of 72' and 74' obtained from krypton-85 data.

The maximum flowing subsurface temperature recorded in the flow string at 8200' was 438°F.

## III. GAS ANALYSIS DATA

A total of 12 gas samples were taken during the flow tests. A complete chemical analysis of these samples was made to determine the percentage of the various methane series hydrocarbons present and to determine the concentration of the two primary diluents, carbon dioxide and hydrogen. These data plotted as mol percent concentration vs. cumulative gas produced are shown in Figure 3.

It is interesting to note that through the production of approximately 375 MMSCF of gas the decline in concentrations of hydrogen and carbon dioxide were essentially parallel, accompanied by an increase in methane. At this point, however, the percentage of carbon dioxide began to increase very gradually from a minimum of 19% to approximately 22% by the end of the third production test. This increase was accompanied by a corresponding decrease in the methane component. The interpretation of this behavior is discussed below in Section IV.

All of the gas samples mentioned above were also analyzed for certain radioactive components, including the two gaseous isotopes, tritium and krypton-85. Figure 4 shows the change in total tritium and krypton-85 concentrations with respect to cumulative gas production. The concentrations of these two isotopes declined in an expected manner and were only about 2% of their initial concentrations at the conclusion of flow testing.

The isotope mercury-203 was also observed in the Rulison gas and was found to decline in concentration in a manner similar to that for krypton-85 and tritium. Chemical analysis of the formation rock near the point of detonation indicated that sufficient mercury was present naturally to produce the minute concentrations of mercury-203 seen in the Rulison gas.

Early calculations were made to determine the volume of vaporized gas bearing rock that would be required to produce the initial concentration of krypton-85 assuming that uniform mixing of the released gas and krypton-85 takes place. These results, based on the theoretical creation of 800 curies of krypton-85, the initial concentration of krypton-85 observed in the gas, 151 picocuries/cc and the presumed reservoir pressure and temperature indicated a cavity radius of 72 feet. Later calculations based on the observed release of 1064 curies of krypton-85 and the observed reservoir pressure and temperature indicated a cavity radius of 74 feet. As previously noted, these dimensions compare very favorably with the pressure analysis results and the information developed by re-entry drilling.

The yield of the Rulison explosive was subsequently calculated to be $43 \pm 8$ kilotons based on the creation of approximately 1113 curies of krypton-85 and on the basis of $25.8 \pm 3.9$ curies krypton-85 per kiloton.[6]

Only 2824 curies of tritium were produced from the well during the flow tests.[5] This is only about 28% of the theoretical 10,000 curies predicted to result from the nuclear explosion.[4] Essentially all of the gaseous tritium was removed from the cavity by the end of the testing, as shown in Figure 4. An accounting of all of the tritium created could not be made, however, because of the large quantity of tritiated water still being recovered at the conclusion of testing and an unknown volume of water remaining in the cavity. It is believed that the boron carbide shield surrounding the nuclear explosive was probably effective in reducing the tritium produced by the explosion to below 10,000 curies, but the lack of a tritium balance has made it difficult to evaluate this effectiveness.

## IV. EVOLUTION AND PRODUCTION OF WATER AND CARBON DIOXIDE

### A. Water

The total volume of water initially in the chimney is believed to have been as much as 30,000 barrels. There has been no way, however, to accurately assess this initial volume. This water was that originally contained in the pore space of the rock, both sand and shale, which was vaporized by the intense heat resulting from the nuclear detonation, plus that water which was contained in the drilling mud lost when the re-entry hole established communication with the chimney. Approximately 15 thousand barrels of water were recovered at the surface during the flow tests, and an additional calculated volume of approximately 6 thousand barrels of water passed through the gas volume measurement system as vapor. At the conclusion of the third production test, approximately 170 barrels of water, liquid and vapor, were still being produced from the well with each MMSCF of gas and diluents being produced. The concentrations of tritium in the produced water remained essentially constant throughout the flow testing, indicating no influx of new water from the producing formation.

As the pressure in the chimney declined, the absorptive capacity of the gas increased, allowing the gas to carry increasing amounts of evolving water vapor to the surface. A part of this vapor condensed in the separation equipment and was measured. The gas which left the separator was assumed to be saturated with water vapor. The amount of water leaving the separator equipment in the vapor phase was estimated using a published correlation of the absorptive capacity of natural gas by Katz et al.(7) This calculated amount of water vapor was added to the amount recovered as liquid to determine the total water content in the production stream. A total of 158 MMSCF of water vapor is estimated to have evolved in the cavity during the flow tests.

Figure 5 shows the daily total water produced per million standard cubic feet of dry gas. A significant change in the rate of water production occurred as the chimney pressure approached 380-400 psia (time period 166-176). This is interpreted as the time when most of the water remaining in the chimney reached its vapor pressure and flashed into steam. Following this, it is believed that additional water continued to flash in the fractured zone as it also reached its vapor pressure. A chimney temperature of 440-445°F is indicated from this event. Pre-shot estimates of cavity temperature were 350-400°F.

As water vapor evolved in the chimney, it added to the volumetric withdrawal from the chimney and at the same time added to the apparent influx of gas into the chimney. In addition, the vaporization of the water in the chimney created additional space available to gas, water vapor and other diluents.

## B. Carbon Dioxide

As the well was produced the hydrogen concentration in the gas declined almost linearly with the cumulative gas production (see Figure 3). The carbon dioxide concentration, however, did not decline in this fashion. Logically, if all of the carbon dioxide and hydrogen were formed at the time of the detonation and were uniformly mixed in the vapor phase, both the carbon dioxide and hydrogen concentration should have declined similarly. The carbon dioxide concentration not only failed to decline commensurately with the hydrogen concentration, but actually began to increase after a cumulative production of at least 375 MMSCF of gas (time period 148).

Laboratory measurements of the relative concentration of carbon-14 in the gas have shown that carbon dioxide was initially formed at the time of detonation but was also generated by heating of the rock subsequent to the detonation. The later evolution of this excess carbon dioxide, which was carbon-14 free, is reflected by the change in concentration seen on Figure 3. This evolution was an addition to the apparent influx of gas into the chimney. A total of 24 MMSCF of carbon dioxide is estimated to have evolved during the flow tests.

Figure 6 shows the measured separator gas gravity with respect to time and also reflects the later evolution of carbon dioxide. The rapid removal of carbon dioxide during the first and second flow tests (time periods 23-31 and 58-76) caused the initial decline in gravity. Once the cavity pressure was appreciably reduced, however, the excess carbon dioxide began to evolve faster than it was being removed such that it brought about the subsequent increase in gravity. The continued decline in hydrogen concentration also contributed to the gravity increase.

## V. ANALYSIS OF WELL PERFORMANCE

A one-dimensional radial flow model[8] was used to simulate well performance. A considerable amount of new programming of this model was necessary to properly incorporate the effects of chimney temperature and varying gas composition on the performance of the well. In addition, it was necessary to simulate the evolution of water vapor, the enlargement of the chimney volume available to gas as a result of the vaporization of water, and the effects of evolution of carbon dioxide.

The volume of void space in the chimney, the properties of the fractured zone, and the properties of the reservoir rock were varied until a match of the subsurface pressure data could be obtained. During the periods of production, it was necessary to continually increase the permeability of the fractured zone in order to obtain a history match. This is interpreted as being indicative that the fractured zone was being cleaned of water as the well was produced. There were indications that the well was still cleaning at the time it was shut in on April 23, 1971.

## VI. PROJECTED WELL PERFORMANCE

The application of the radial flow model to simulate the nuclear stimulated reservoir characteristics resulted in the match of the bottom hole pressure data shown in Figure 7. From this, predictions of well performance have been made. Figure 8a describes the predicted rate behavior for the nuclear stimulated well, assuming that flow was initiated at original reservoir conditions and at a rate of 1000 MCF of gas per day. Figure 8b shows the predicted cumulative production of gas from this well expressed in billion cubic feet (BCF) and as the percent of gas in place recovered from the stimulated interval. These results compare reasonably well with the recoveries predicted from the pre-shot reservoir analysis.[9]

Two configurations of net pay thickness (h) have been used in making these predictions, one a constant thickness, the other a decreasing thickness. In the latter instance, the pay thickness was decreased as the drainage radius increased in a mode similar to the model described by Knutson et al[10]. The midpoint between this model result and a constant thickness was actually used for the predictions shown here. Other variations were also investigated but are not reported in this paper.

## VII. SUMMARY

The objectives of Project Rulison were to determine the technical and economic feasibility of stimulating the Mesaverde formation in the Rulison Field with a nuclear explosive. The results to date indicate that the technical objectives have been successfully achieved. The economic evaluation is still in progress and will be reported in due course.

The results of Project Rulison should aid in the feasibility assessment of applying this technology in other similar gas bearing reservoirs. It is apparent, for instance, that for every reservoir type there is a gas price that would permit the economical recovery of the gas. It is believed that the results of Project Rulison will allow a more precise evaluation of this factor.

No other specific conclusions have been drawn from the results of Project Rulison because the technical information and data must be interpreted by others in light of their own technical and economic framework. The technical interpretations reported herein may be revised at a later time as new information and other theories are developed.

## VIII. FUTURE PLANS

Austral Oil Company and Colorado Interstate Gas Company have initiated a study by Oak Ridge National Laboratory to assess the potential radiation exposure that might result from the distribution and use of Rulison gas under various marketing conditions. These studies are expected to be completed before the end of calendar year 1971. These studies are expected to confirm that exposures which might result from the use of Rulison gas will be only a small fraction of the total average annual exposure to man from all sources of about 100-125 millirem. With these results the two industrial parties plan to initiate the actions necessary to permit the sale of gas from the Rulison nuclear stimulated well.

## IX. ACKNOWLEDGEMENTS

The author wishes to express his gratitude to the firms of DeGolyer and MacNaughton, Dallas, Texas, and Computer Technical Services, Inc., Dallas, Texas, for their assistance in preparing the material presented here. Recognition is also given to the members of the Project Rulison Technical Committee who played an important role in the development of the Rulison evaluations.

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4. "Project Rulison, Post-Shot Plans and Evaluations", NVO-61, U. S. Atomic Energy Commission, December 1969.

5. "Project Rulison, Interim Radioactivity Report, Third Production Test", R. L. Gotchy, OPNE-NVOO, U. S. Atomic Energy Commission, May 1971.

6. Memorandum, May 28, 1971, from Dr. R. Lee Aamodt, Los Alamos Scientific Laboratory (LASL) to Dr. Wm. Ogle, J-Division Leader, LASL, with enclosures.

7. Handbook of Natural Gas Engineering (p. 196), Donald L. Katz, et al, McGraw-Hill, 1959.

8. Author's Note: Description of this radial flow model does not appear in the literature at this time. The model is owned by Computer Technical Services, Inc., Dallas, Texas.

9. "Project Rulison: A Preliminary Report", Miles Reynolds, Jr., et al (p. 622-623), Engineering with Nuclear Explosives (Vol. I), ANS Topical Meeting, Las Vegas, Nevada, January 1970.

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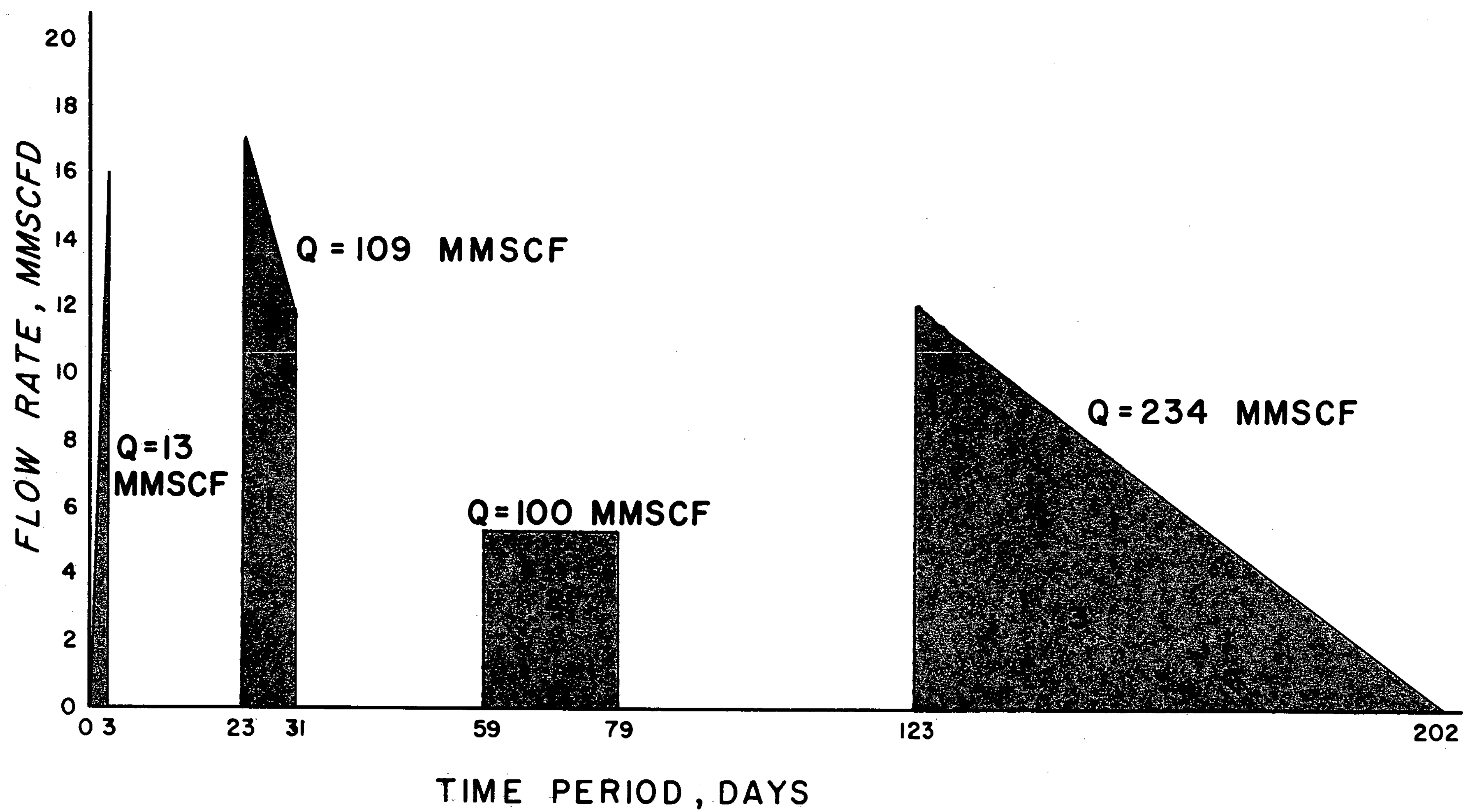
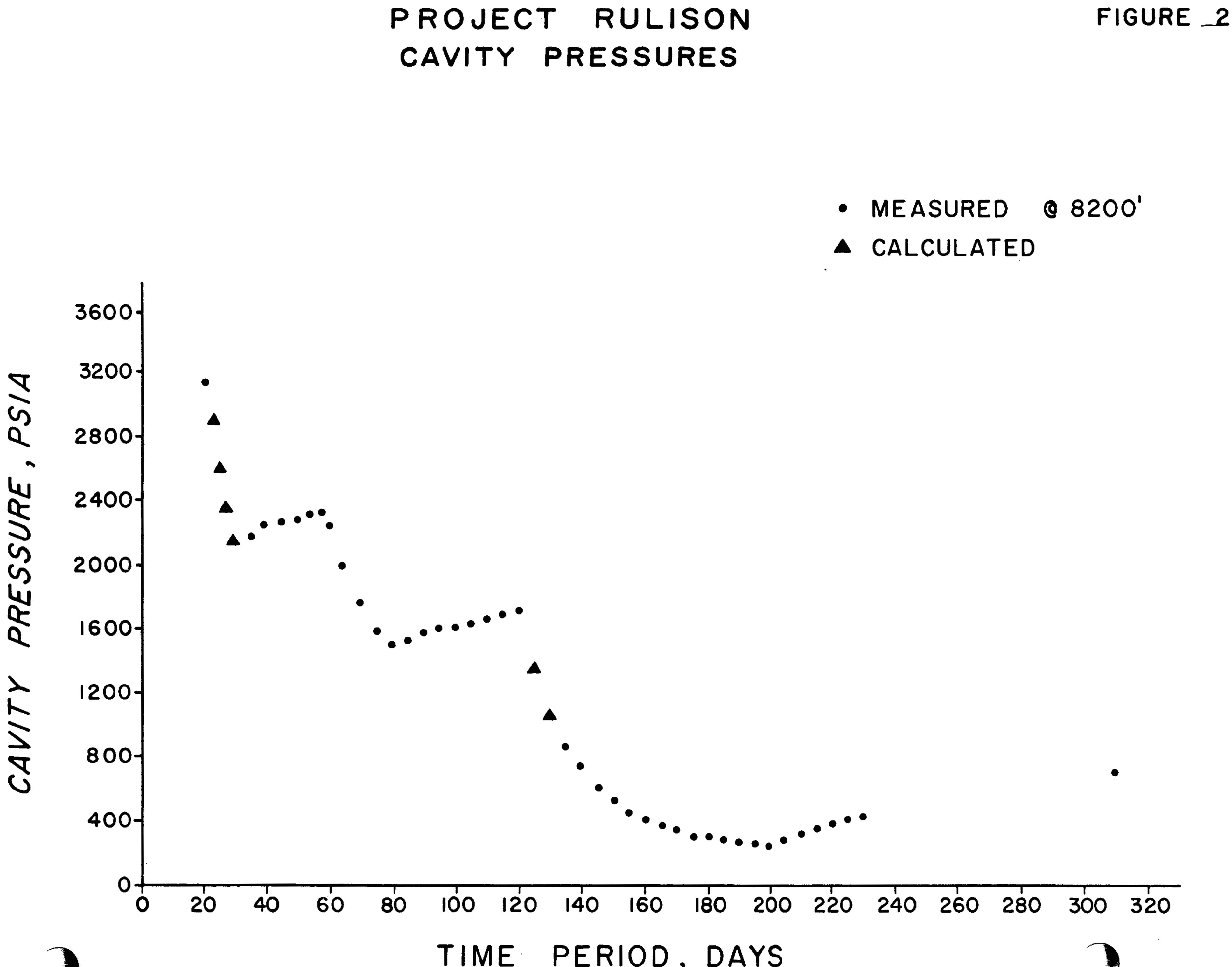
# PROJECT RULISON
## FLOW TESTS

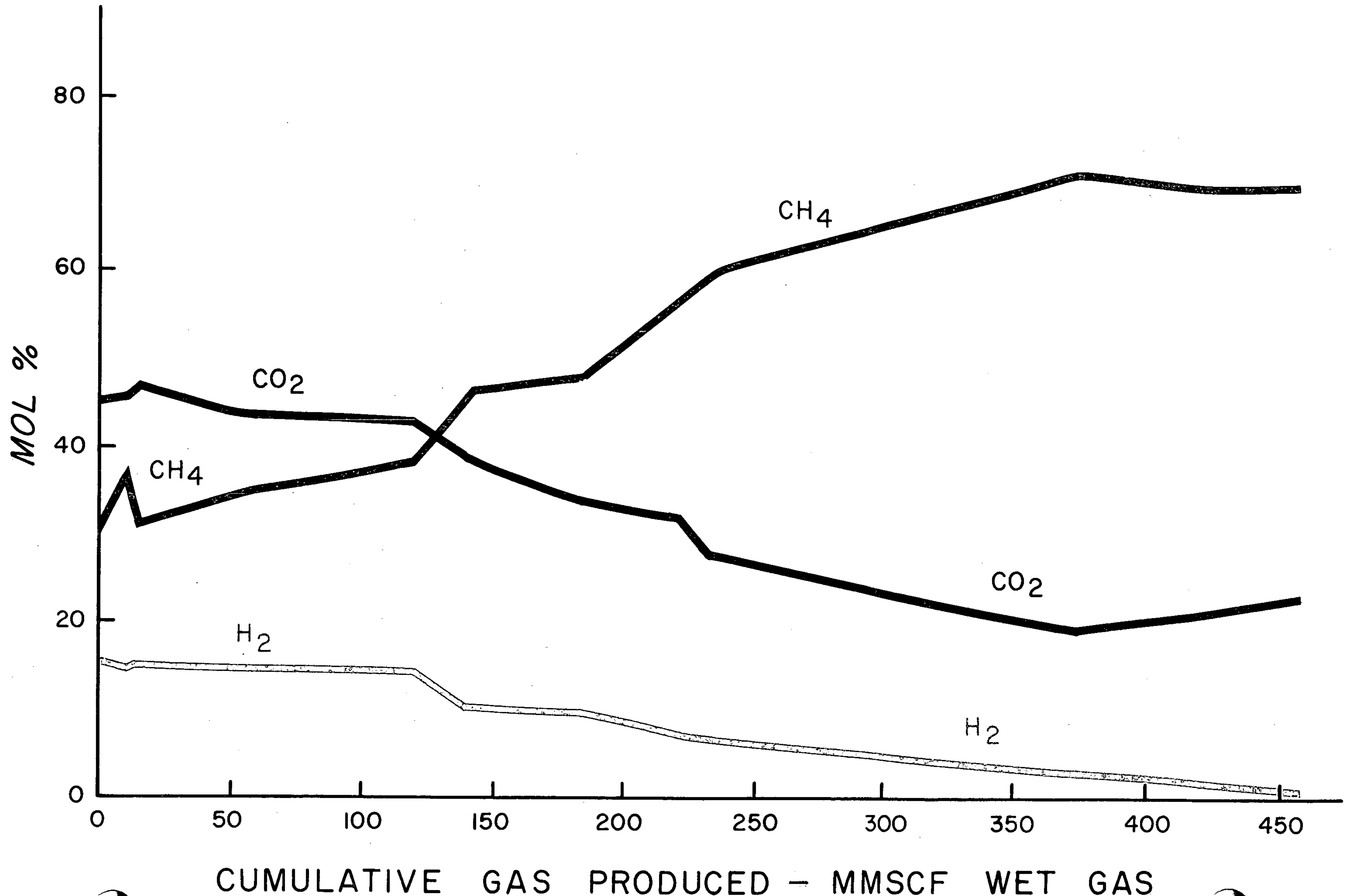




PROJECT RULISON
CAVITY PRESSURES
FIGURE 2
MEASURED @ 8200'
CALCULATED
CAVITY PRESSURE, PSIA
0
400
800
1200
1600
2000
2400
2800
3200
3600
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
TIME PERIOD, DAYS

FIGURE 3

# PROJECT RULISON
## CHEMICAL ANALYSIS DATA



# PROJECT RULISON — FIGURE 4
## RADIOCHEMICAL ANALYSIS DATA

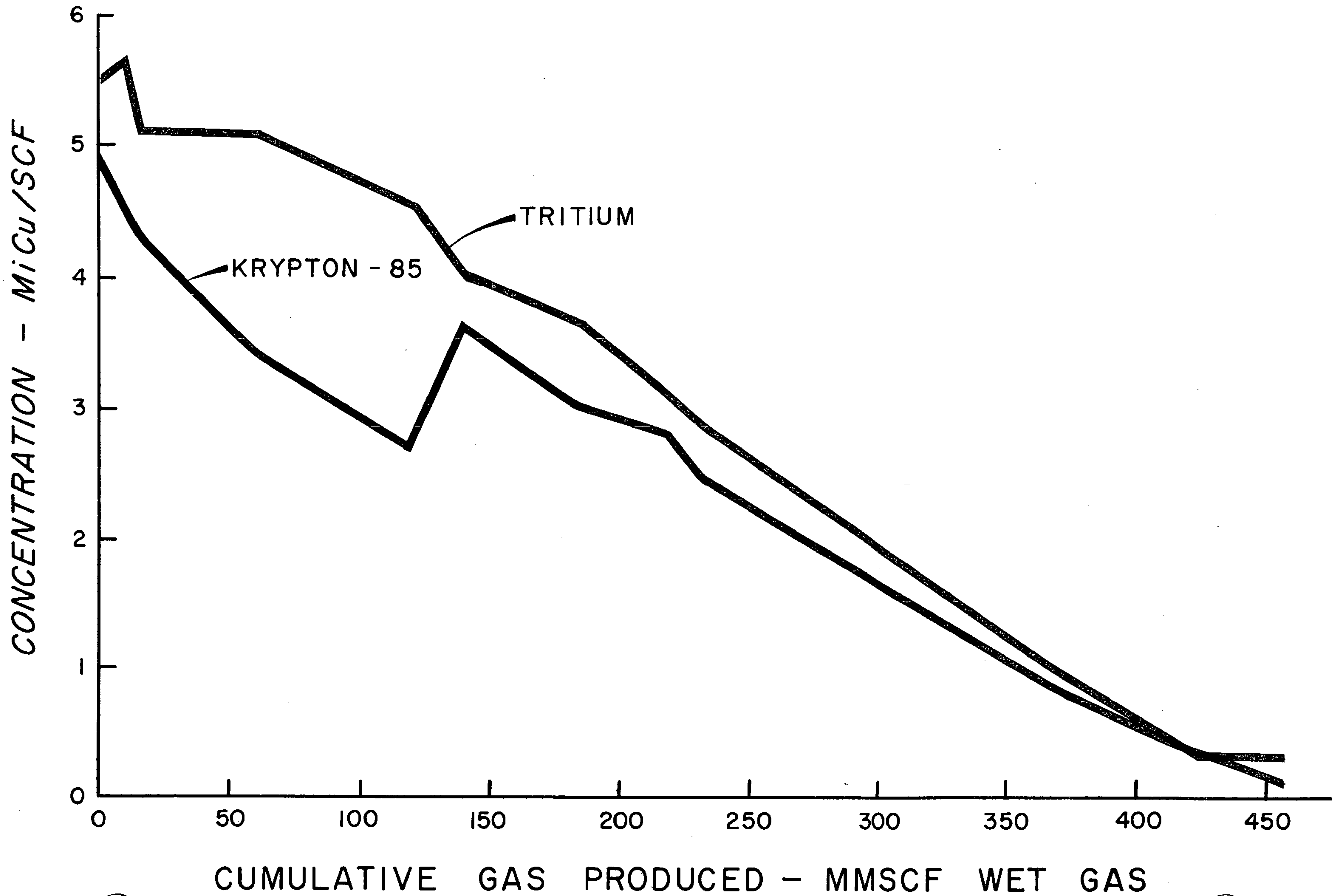
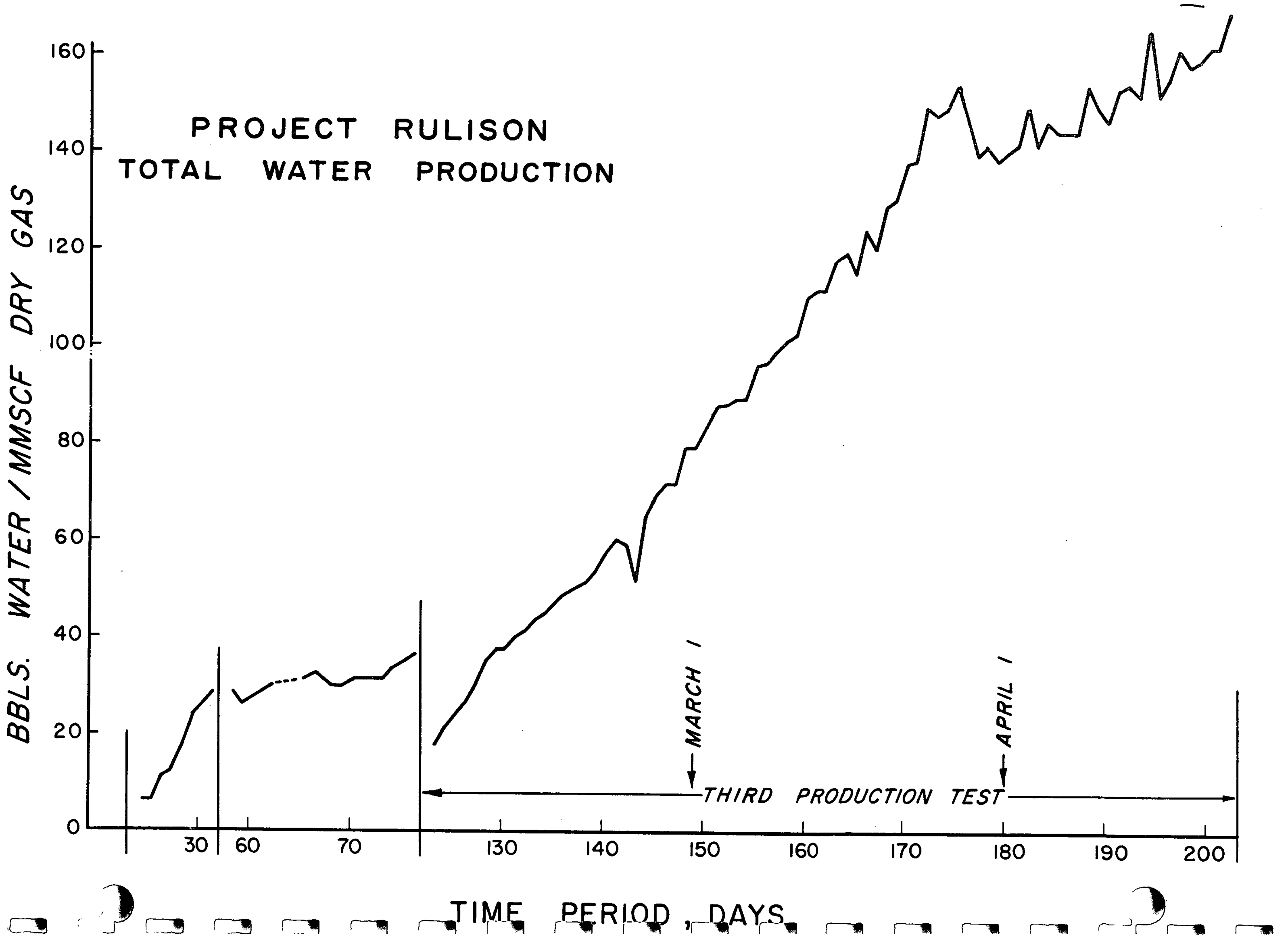
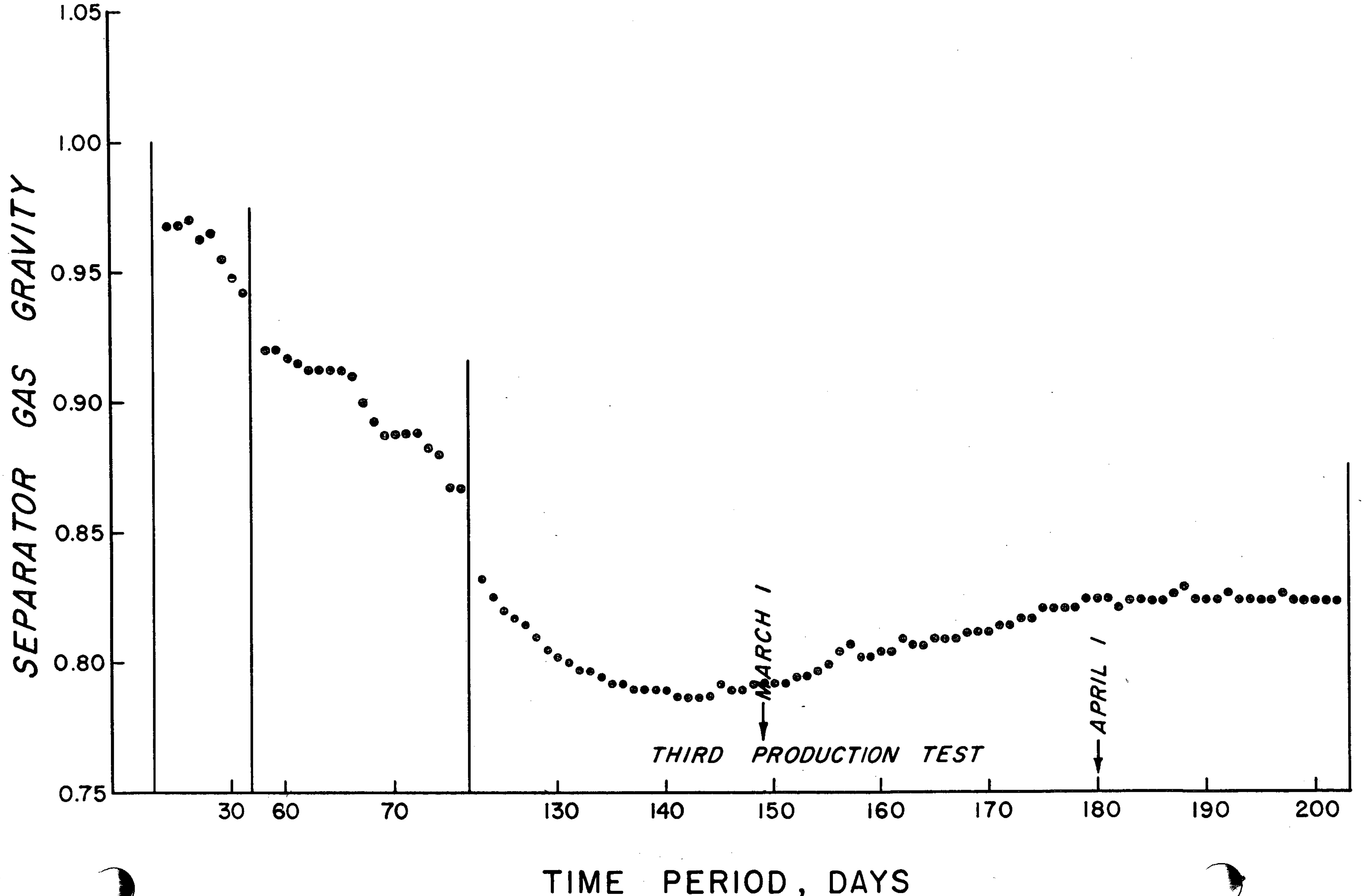


FIGURE 5


PROJECT RULISON
TOTAL WATER PRODUCTION
BBLS. WATER / MMSCF DRY GAS
0
20
40
60
80
100
120
140
160
30
60
70
130
140
150
160
170
180
190
200
MARCH 1
APRIL 1
THIRD PRODUCTION TEST
TIME PERIOD, DAYS

PROJECT RULISON
SEPARATOR GAS GRAVITY

FIGURE 6



# PROJECT RULISON
# PRESSURE HISTORY MATCH

FIGURE 7

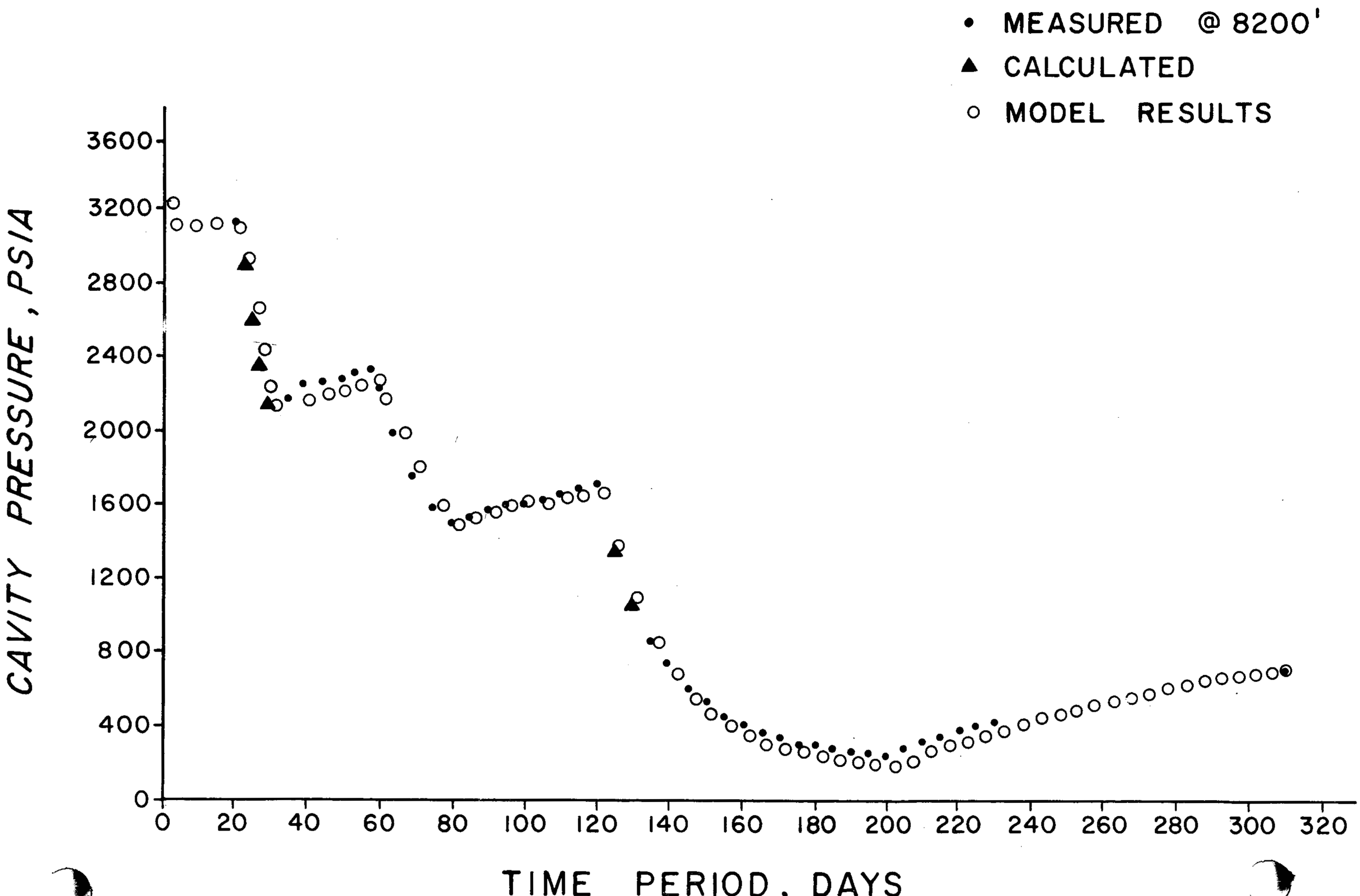


FIGURE 8a

# PROJECT RULISON TEST WELL
## PREDICTED RATE DECLINE

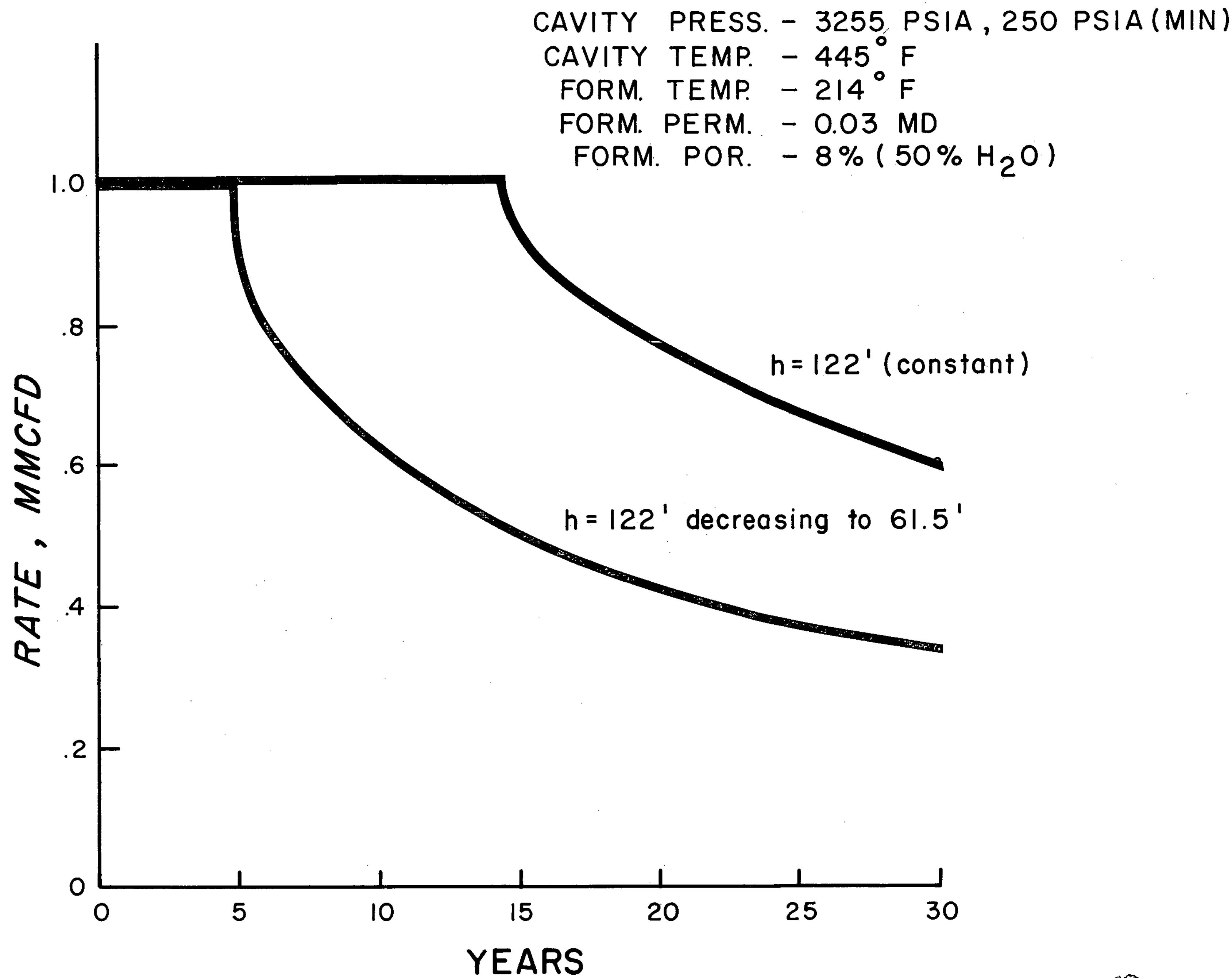


FIGURE 8b

# PROJECT RULISON TEST WELL
## PREDICTED GAS RECOVERY